NUMERICAL SURFACE FLOW VISUALIZATION

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Abstract

Surface oil flow is an experimental flow visualization technique that depicts the surface flow pattern near the body of the model. Traditionally, a particle tracking technique that generates streamlines near the model body is used to depict surface flows in CFD flow simulations. In this paper, we compared surface flows represented by streamlines with those represented by a texture technique known as Line Integral Convolution (LIC). We found that streamlines used to depict surface flows are discontinuous in general and the quality of the surface flow pattern is highly dependent on the placement of the streamlines. Whereas, the LIC technique clearly depicts surface flows that closely resemble surface oil flows. We also found that surface flows near regions of vortex structures and saddle points are not best shown using the streamline technique compared to the LIC technique. For unsteady flow simulations, we compared streaklines with a new texture synthesis technique called Unsteady Flow Line Integral Convolution (UFLIC) that we have recently developed. UFLIC accurately reveals the dynamic behavior of unsteady surface flows during animation.

Introduction

Surface oil flows are used in experimental flow visualization to represent surface flow patterns near the body of the model. This technique is attractive because it gives a good impression of the flow patterns near the model body and is effective for depicting flow separation and re-attachment lines. Surprisingly, there has been relatively few developments of this technique in numerical flow visualization. CFD scientists commonly use streamlines, which are released from each grid point near the grid surface, to observe surface flows. In the past two decades, there have been several well-known visualization software programs that support a suite of numerical flow visualization techniques. Some of these techniques include: vector plots, contours (lines and surfaces), particle traces, and cutting planes. Many of these programs do not generate surface flows that resemble those seen in experiments.

In the computer graphics community, a texture synthesis technique called Line Integral Convolution (LIC) that generates realistic looking surface flows in uniform Cartesian grids has been proposed by Cabral and Leedom [1]. Their technique can clearly depict surface flows of CFD flow simulations by producing textures with directional patterns based on the underlying flow fields.

We refer to the surface flows depicted by streamlines and the LIC technique as *steady surface flows*. We have developed a new texture synthesis technique called Unsteady Flow Line Integral Convolution (UFLIC) that generates surface flows in unsteady flow fields [2]. We refer to the resulting flow pattern as *unsteady surface flows*. Our technique is very effective in depicting flow dynamics.

In this paper, we first discuss the advantages and disadvantages of using streamlines to represent surface flows. We then describe the LIC technique for generating steady surface flows. Next, we compare steady surface flows generated by the streamline method with those generated by the LIC technique. We then discuss unsteady surface flow visualization using streaklines and introduce UFLIC for creating unsteady surface flows. Finally, we compare unsteady surface flows depicted by UFLIC and streaklines.

Streamlines

Streamlines are very popular for visualizing flow fields and are commonly used for representing surface flow patterns. By computing a local streamline at each grid point, the surface flow pattern can be observed. This method is relatively simple and straightforward. There are, however, some drawbacks. One drawback is the discreteness of the streamlines; this does not give a continuous flow line covering a large region of the flow. Another disadvantage is that the outcome of the surface flow is based on the placement of the seed points where the streamlines are computed.

A common practice is to compute streamlines at every grid point on the grid surface. This works fine if the grid points are uniformly distributed. However, some grids are complex and often have dense grid points near the boundary of the model body. Computing streamlines at every grid point in this case could result in artifacts due to variations in the grid spacing. A possible solution is to use randomly distributed seed points on the grid surface. The overall impression of the flow would still depend on the distribution of the seed points. A better placement would be to use more seed points near regions where the flow varies rapidly and fewer seed points at regions where the flow does not vary too much. However, this would require prior knowledge of the flow field and additional preprocessing.

Line Integral Convolution

Line Integral Convolution (LIC) is an effective texture synthesis technique which generates texture mapped images with surface flow like patterns [1]. The basic idea is to take an image with random white noise and a vector field defined over the image as the input. The image is then blurred such that it depicts a texture that reveals the flow direction everywhere in the given vector field. Figure 1 shows the input and the output images from this technique. The algorithm works as follows. For each pixel in the image, a local streamline is computed from the pixel location in both the positive and negative directions by a fixed length called the convolution length. A weighted average of the intensities of the pixels along the streamline is then computed. The weighted average is computed using a convolution kernel, which is a low-pass filter function. The calculated intensity is the new intensity of the pixel. Because each pixel's new intensity is based on the intensities of the pixels along the local streamline, nearby pixels on the same streamline will have very close intensity values. Thus, the resulting image depicts the flow lines accurately.

The convolution length controls how continuous the flow lines appear in the final texture image. The longer the convolution length is, the more continuous the flow lines will be.

LIC is an attractive method for generating surface flows because it is image space based rather than object space based. That is, the resulting surface flow does not depend on the placement of the seed points. Thus, prior knowledge of the flow field is not required. Furthermore, flow lines are continuous and the flow features are easy to see.

Another texture synthesis technique that has been used to generate surface flows is known as spot noise [3]. This technique displays spots or dots randomly over the grid surface, and each spot is shaded with random intensity. The shape and size of the spot is proportional to the velocity direction and magnitude at that location. The quality of the surface flow depends on the shape of the spots and the number of spots used. The resulting flow lines may not be continuous since the spots are discrete. Spot bending is a new enhancement to create flow lines that give a more accurate representation of the flow [4]. In general, we found LIC generates more continuous flow lines than spot noise.

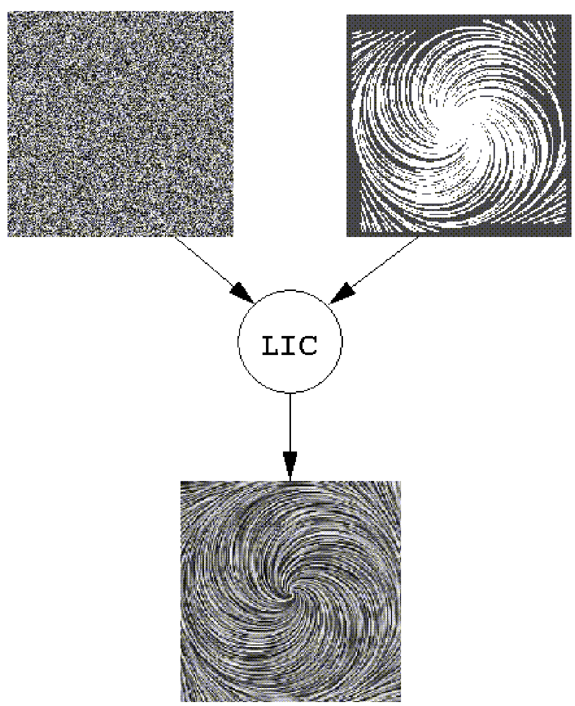

Figure 1. LIC generates surface flows based on a random white noise image and a vector field as the inputs.

Steady Surface Flow Comparisons

In this section, we compare surface flows generated from streamlines with those generated by the LIC technique. We used a program called Animated Flow Line Integral Convolution (AFLIC) to compute steady surface flows [5]. Our first data set is from an unsteady flow simulation about a 65-degree sweep delta wing at 0.27 Mach Number with zero roll angle at 30 degrees angle of attack [6]. Although the flow is unsteady, for comparison purposes we will use one time step of the data. Figures 2a and 2b show surface flows on the delta wing computed using streamlines and the LIC technique, respectively. The flow lines are more continuous in Figure 2b than Figure 2a. Streamlines shown in Figure 2a depict the flow reattachment lines, however, they do not reveal flow separation lines clearly. In a closed-up view, the LIC technique reveals both separation and reattachment lines. The vortex structures are more evident in the LIC technique than those shown in the streamlines. Different selections of seed points were attempted to generate the surface flow shown in Figure 2a. For the figure, streamlines were computed at every other grid points. We have tried to compute the streamline at every grid point, but the resulting image becomes very cluttered with streamlines. Another factor that determines the resulting quality of the streamlines is the length of the streamlines. For the images generated in this paper, we used a maximum particle trace length of 30.

Figures 3a and 3b depict steady surface flows computed using streamlines and the LIC technique on the vertical tail of an F/A-18 fighter aircraft. The saddle points at the upper left and the lower center of the tail are very clear in the LIC technique (Figure 3b). Due to the grid resolution, the saddle points are not depicted clearly in Figure 3a. In Figure 4, a different time step was chosen. Comparing Figures 4a and 4b, the saddle point near the center of the tail is also not shown clearly with streamlines.

One disadvantage of the LIC technique is that the resolution of the surface flow is based on the texture map resolution, hence some flow lines may appear to be jagged in a close-up view. Since the resolution of the texture map is changeable by the user, we found this is not a concern. Furthermore, anti-aliasing techniques can be used if needed. Another disadvantage of the current LIC technique is that because the texture map is monochrome, sometimes it may be difficult to see flow separations and reattachments easily. For example, in Figure 2b, these features, which occur along the leading edge of the wing, are not very clear because of the bird's-eye view of the delta wing. To resolve this problem, Okada and Kao [5] have proposed several enhancement techniques to highlight flow features such as flow separation and reattachment. One technique is to color the surface flow based on the velocity direction. This captures the flow features very effectively. We refer the reader to the paper for a detailed description of the technique.

Streaklines

Unsteady flow simulations are becoming feasible because of advances in computing technology. It is desirable to study surface flows in unsteady flow fields. Although it is possible to apply an instantaneous surface flow technique, such as streamlines or LIC, to each time step of the unsteady data one at a time and then animate the resulting surface flows, this may not depict continuous flow motion. Both the LIC and the streamline methods capture the flow pattern at an instant in time and do not consider the time variable in the calculation. For example, instead of seeing a vortex spirals over time, one may only see the displacement of the spiraling vortex. Furthermore, since the time variable is not considered in the calculation, animating instantaneous surface flows may not accurately depict time-varying phenomena in the unsteady flow. One example is the dynamics of vortex shedding and formation. This issue is also discussed in [7], where comparisons of streamlines, streaklines, and timelines were reported.

In order to visualize surface flows in unsteady flow fields, time-dependent particle traces should be used. Analogous to using streamlines for steady surface flow, we can use streaklines for unsteady surface flows. Streaklines are computed by releasing particles continuously from fixed seed points and displaying particles from the most recent N time steps, where N is specified by the user. A good range for N is between 10 and 20. By releasing particles from the grid surface and tracking them over time, the surface flow pattern can be generated. Using streaklines to visualize unsteady surface flow is fairly straightforward. However, as with streamlines, the placement of the seed points is a major factor in determining the quality of the unsteady surface flow.

Unsteady Flow Line Integral Convolution (UFLIC)

We have developed an algorithm for unsteady surface flows. The algorithm generates LIC like images and uses time-dependent particle traces for the convolution. The resulting images reveal realistic looking surface flows that evolve over time. Unlike LIC, which is based on streamlines, UFLIC is based on time-dependent particle traces. UFLIC incorporates time into the convolution and tracks the image texture over time to create continuous flow motions.

The core of the UFLIC algorithm is based on two main concepts: time-accurate value depositing and successive feed forward. With time-accurate value depositing, each pixel advects through the flow field and deposits its image value with a time stamp. To compute the intensity of a pixel at the current time step, a weighted average of the intensities of all pixels which pass through that pixel with the same time stamp is computed. In order to provide continuous flow motion over time, the output image of the current time step is used as the input image for the convolution at the next time step. We referred to this concept as successive feed forward. A potential problem with this method is that the image may gradually lose contrast as time progresses since LIC is a low pass filter. In UFLIC, we use a high pass filter to enhance the current image contrast before using it in the next time step.

Overall, UFLIC generates highly coherent surface flows between consecutive time frames because the flow texture is convolved and advected continuously through space and time. A detailed description of the UFLIC algorithm can be found in [2].

Unsteady Surface Flow Comparison

In this section, we compare unsteady surface flows using the techniques described in the previous sections. For our first comparison, an unsteady flow simulation about the delta wing is used. The flow is unsteady with vortex breakdown. Figure 5 shows surface flows computed using streamlines, streaklines, UFLIC, and LIC. The best way to compare these four techniques is by animation since the flow is unsteady. In the animation, the dynamics of the surface flow are best revealed by the streaklines and UFLIC methods. We have found that streamlines and LIC are useful for depicting the flow at an instant in time; however, they do not necessarily show the time-varying phenomena in the flow accurately. In the surface flows generated by the UFLIC technique, we found that the flow lines become blurry in the region where the flow changes rapidly. This corresponds to the physical phenomena in the experiment because as the flow direction changes rapidly, the oil spreads out over the model surface and leaves no discernible flow line traces on the surface.

For our second comparison, an unsteady flow simulation of the F/A-18 fighter aircraft was used. At high angle of attack, tail buffet occurs when the vertical tails are immersed in the unsteady flow from leading-edge extension vortices [8]. The unsteadiness of the flow at the tails is very much apparent on the surface of the tail. Figure 6 shows surface flows generated by the four techniques discussed previously. Both the streaklines and UFLIC show the development of the flow over time, whereas streamlines and LIC depict the behavior of the flow at an instant in time only.

Software

Based on our new algorithm, a software program called GLIC (Graphical Line Integral Convolution) is currently being developed at NASA Ames Research Center to support visualization of instantaneous and unsteady surface flows. It provides a graphical user interface to allow interactive parameter updates, viewing control, and animation playback. GLIC supports multi-tasking, which implies surface flow computation and interactive user parameter updates can be concurrent. Presently, the program runs on SGI workstations only. GLIC allows the user to save the computed surface flow for playback, which is extremely useful when analyzing unsteady flows because it allows scientists to review the results without recalculation.

Conclusion

We have compared particle tracing and the line integral convolution techniques for surface flow visualization. Although particle tracing has been commonly used in the CFD community, we showed that the LIC technique depicts continuous flow lines which are not shown with traditional particle tracing techniques. We have also compared unsteady surface flows represented by streaklines and UFLIC. The results showed that UFLIC depicts a better impression of the flow dynamics during the animation.

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